How Common is Energetic ^{3}He in the Inner Heliosphere?

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Abstract. Using data from the SIS and ULEIS instruments on the Advanced Composition Explorer (ACE) we have identified periods during which energetic ^{3}He is present in near-Earth interplanetary space between November 1997 and May 2002. The data, which cover the energy intervals 0.2–1 MeV/nuc (ULEIS) and 4.5–16.3 MeV/nuc (SIS), show that ^{3}He is present a significant fraction of the time, as would be required if these suprathermal particles were the major source of the ^{3}He being accelerated by shocks in the interplanetary medium. Specifically, we find that energetic ^{3}He is present at least $\sim$ 60% of the time, and perhaps significantly more often.

INTRODUCTION

The existence in some solar energetic particle (SEP) events of large enhancements of the ^{3}He/^{4}He abundance ratio, sometimes by factors $> 10^4$ over the solar-wind ratio of 4×10^{-4}, has been a subject of great interest since the discovery of these "^{3}He-rich events" in the 1970s (see, e.g., [1] and references therein). The extreme isotopic fractionation of helium in these events is thought to occur as the result of some resonant form of wave heating and/or acceleration in solar flares (see [1] for references). Adopting the commonly-used terminology, we will call these events "impulsive"[1] to distinguish them from "gradual" events (see below).

Measurements made by new instruments with improved mass resolution and large collecting power on the Advanced Composition Explorer (ACE) [2, 3] have shown that previous empirical definitions of ^{3}He-rich events need to be broadened. Specifically, it has been found that ^{3}He/^{4}He enhancement factors range from < 10 to $> 10^4$. The threshold previously used to define these events, ^{3}He/^{4}He> 0.1, was simply related to the inability of earlier instruments to identify lower fractional abundances of ^{3}He.

In addition, ACE measurements [5, 4, 6, 7, 8] have shown that sizeable enhancements of the ^{3}He/^{4}He ratio also occur in a significant fraction of large gradual SEP events, in which particles are believed to be accelerated not as a direct result of reconnection in solar flares but rather by shocks driven by coronal mass ejections (CMEs) as they propagate through the solar corona and interplanetary space. In some gradual events ^{3}He/^{4}He ratios > 0.01 have been measured.

Mason et al. [6] addressed the question of the origin of the ^{3}He excesses in these gradual events, proposing that a background of energetic ^{3}He particles from numerous small impulsive events is commonly present in the inner heliosphere and that a coronal/interplanetary shock encountering this remnant impulsive material will accelerate these suprathermal particles more efficiently than particles from the solar-wind thermal distribution. Thus one could obtain excesses, relative to the solar wind, of ^{3}He and of other ions (e.g., Fe) that tend to be enhanced in impulsive events. In this model, the enhancement of ^{3}He depends on the occurrence of appropriately-located impulsive SEP events in the hours or days preceding the passage of the shock.

Desai et al. [9] found enhanced abundances of energetic ^{3}He in more than 40% of particle events associ-

[1] In this paper we treat "impulsive" as a synonym for "^{3}He-rich".

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Table 1
Energy Intervals

ULEIS-L	0.2-0.4 MeV/nuc
ULEIS-H	0.4-1.0 MeV/nuc
SIS-L	4.5-7.6 MeV/nuc
SIS-H	7.6-16.3 MeV/nuc

ated with the passage of interplanetary shocks near Earth. Mewaldt (private communication, 2002; see also [4, 8]) found a similar fraction of large, gradual SEP events having significant ^{3}He excesses. In the events studied by Mewaldt and collaborators, acceleration is attributed to CME-driven shocks relatively close to the Sun. One possible explanation of these two results is that energetic ^{3}He is present and available for further acceleration in the interplanetary medium a sizeable fraction of the time and over a sizeable range of heliocentric radii.

In this paper we examine the Mason et al. model [6] for the origin of shock-accelerated ^{3}He by directly measuring how frequently energetic ^{3}He is present in the interplanetary medium near Earth.

OBSERVATIONS

The present study uses data from two instruments on ACE that measure helium isotopes in complementary energy intervals, the Ultra-Low-Energy Isotope Spectrometer (ULEIS) [3] and the Solar Isotope Spectrometer (SIS) [2]. Each data set was divided into a low-energy (L) and a high-energy (H) interval as indicated in Table 1. For each instrument the lower-energy interval provides the best statistical accuracy while the higher-energy interval offers improved mass resolution and background rejection.

In order to identify time periods with ^{3}He present, plots of measured particle mass vs. time were made for each of the four energy intervals. An example is shown in Figure 1 for one solar rotation in late 1999 (Bartels rotation 2271). In regions of the plot having low densities of particles, each detected particle is indicated by an individual dot. Where densities are higher (e.g., along the mass 4 line near the maxima of SEP events) intensities are indicated by a grey scale averaged over rectangles encompassing 1 hr $\times$ 0.05 amu. Using similar plots, we partitioned the data for Bartels rotations 2241 through 2302 (September 1997 to April 2002) into time intervals with durations ranging from 0.25 to 10.5 days during which the characteristics of the He isotope fluxes remained relatively constant. In each interval and in each of the four energy ranges the observations were subjectively assigned one of 7 classifications, as defined in Table 2. The classifications assigned for periods in rotation 2271 are indicated along the top of Figure 1.

Table 2
Time Interval Categorization Scheme

ID	Definition
0	no clear ^{3}He
1	low-rate ^{3}He, SEP events not distinguishable
2	^{3}He-rich SEP event
3	^{3}He event, possibly continuation
4	^{3}He event, possibly overlapping events
5	probable ^{3}He, contaminated by spillover
6	too much spillover to distinguish real ^{3}He

Although the ^{3}He/^{4}He ratio is of interest in individual impulsive events, this ratio is not particularly useful for determining the presence of ^{3}He during a general time interval, since one very commonly encounters ^{3}He-rich events during which the ^{4}He flux is dominated by particles from preceding events. An example is seen on days 336–337 in Figure 1. Thus we based our classifications only on the ^{3}He observations. Clearly our ability to detect the presence of small ^{3}He fluxes is limited by the sensitivity of the instruments and the duration of the averaging interval. For reference, the ^{3}He intensities corresponding to one event recorded per hour in SIS and ULEIS are $\sim 2\times10^{-6}$ and $\sim 5\times10^{-3}$ particles/cm^2-sr-s-MeV/nuc, respectively. There are periods (e.g., days 351–355 in SIS) where no more than a few ^{3}He particles are detected per day. As shown by the upper set of mass histograms in Figure 2 (and also evident in Fig. 1) genuine ^{3}He signals can be observed during such periods, but the count rates are too low to distinguish individual ^{3}He-rich SEP events. In fact, near solar minimum (1997–98) the ^{3}He observed at SIS energies may be dominated by galactic cosmic-ray ^{3}He that has undergone adiabatic deceleration entering the heliosphere. The lower histograms in Figure 2 are from such a solar-minimum period.

The ^{3}He observations have a complex time structure and it is frequently not possible to determine whether a period of enhanced ^{3}He intensity (e.g., days 343–349 in Fig. 1) is attributable to multiple ^{3}He injections at the Sun or propagation effects. These complexities have been discussed by Mazur et al. [10]. In fact, it is possible that different sources of ^{3}He are sometimes being observed at the different energies, particularly since transit times from the Sun to Earth differ by about 0.3 days over the energy range we are considering, even in the absence of scattering.

In both SIS and ULEIS, instrumental effects can cause misidentification of a small fraction of the detected ^{4}He as ^{3}He. During some periods (e.g., ULEIS-H on day 338–339.5) there is a reasonable indication of a real ^{3}He contribution, together with some spillover. During other times (e.g., ULEIS-L and SIS-L during this same period)

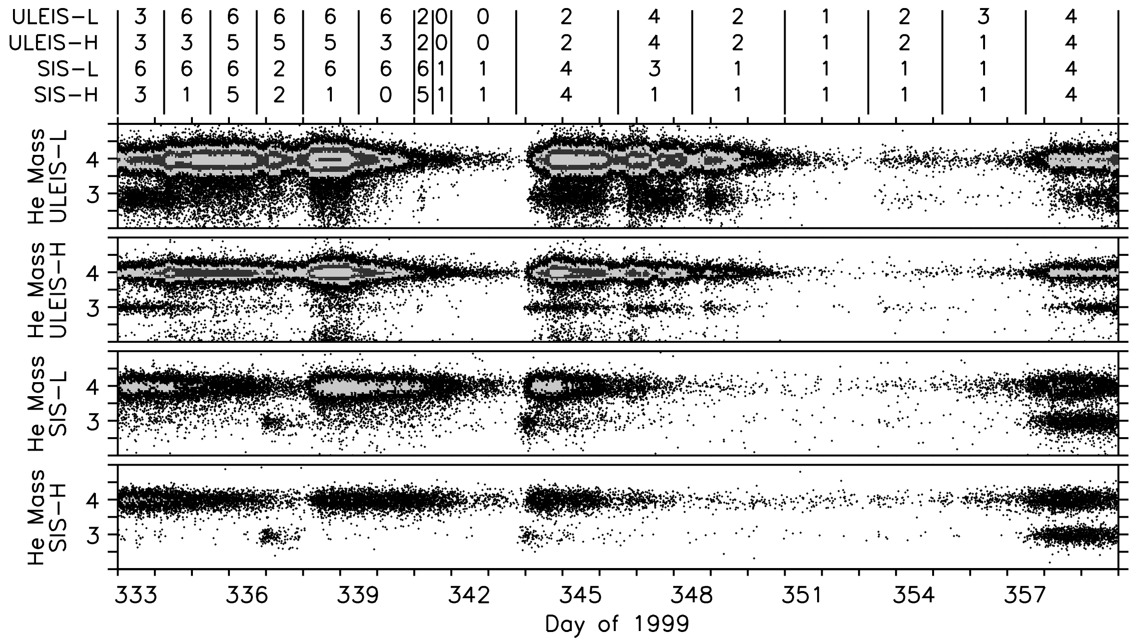

FIGURE 1. Measured He mass vs. time for detected particles in 4 energy intervals. Numbers above the plots indicate how various time intervals were classified (see text). Grey shading is used in portions of the plots where event densities are highest.

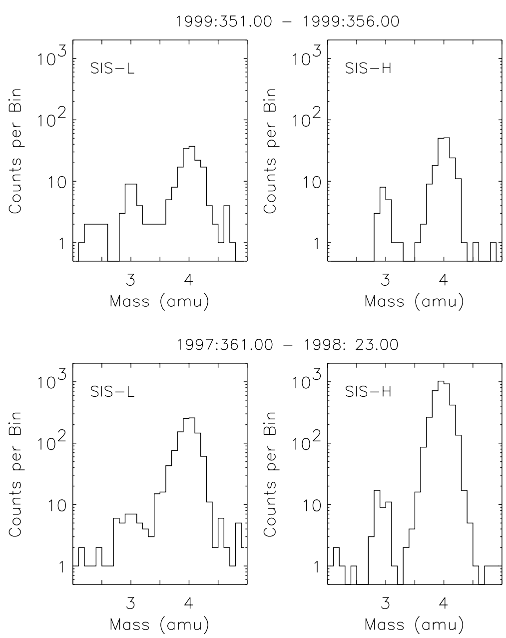

FIGURE 2. SIS He mass histograms from low-intensity periods at solar maximum (upper panels) and solar minimum (lower panels).

the spillover obscures any ^{3}He that may be present.

Using the assigned classifications, we derived limits on the fraction of the time that energetic ^{3}He is present. A very conservative lower limit is obtained by including

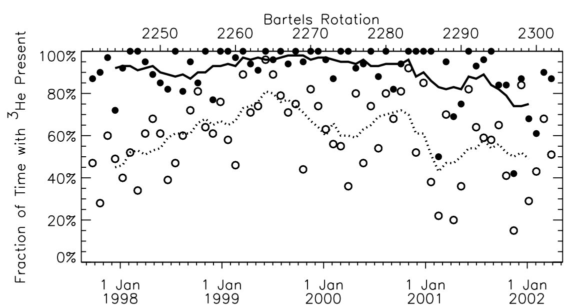

FIGURE 3. Fraction of time with ^{3}He present. Points are shown for individual Bartels rotations; lines show running average over 6 rotations. Unfilled circles and dotted line: unambiguous ^{3}He (categories 2–4); filled circles and solid line: probable ^{3}He (categories 1 and 5) also included.

only times which fall in category 2, 3, or 4 for at least one of the four energy intervals. In these categories there is an unambiguous ^{3}He enhancement. This limit is plotted for each Bartels rotation as unfilled circles in Figure 3. The dotted curve shows the running average over 6 Bartels rotations.

A less-conservative limit is obtained by also including times in categories 1 or 5. This limit is indicated by the filled circles and solid line in Figure 3. We emphasize that these values are also best thought of as lower limits. Intervals in category 5 (as opposed to category 6) have low-enough levels of spillover that the presence of actual ^{3}He is probable. Category-1 intervals have clear ^{3}He, but at levels too low to distinguish distinct SEP events.

DISCUSSION

The more-conservative limit (dotted line) plotted in Figure 3 indicates that ^{3}He in the energy interval studied was present $\sim (60 \pm 20)$% of the time over the period from November 1997 to May 2002. This is similar to the fraction of interplanetary shock events in which Desai et al. [9] report ^{3}He acceleration. However, we note that the ^{3}He observed by Desai et al. is accelerated primarily from suprathermal particles less energetic than those investigated here. We also point out that when we use our looser criterion for identifying periods with ^{3}He, we find that in a sizeable fraction of the solar rotations studied there is ^{3}He present virtually all the time (filled circles plotted along the 100% line in Fig. 3).

The distribution in time, space, and energy of ^{3}He originating in impulsive SEP events is probably quite complex. As the particles propagate out from the Sun their spatial distribution broadens due to geometry, velocity dispersion, and scattering. Scattering from magnetic structures in the expanding solar wind also causes adiabatic energy loss, while shocks can increase particle energies. Thus it is not straightforward to infer from our observations the fraction of time that CME-driven shocks would encounter energetic ^{3}He at a few solar radii. Furthermore, particles could be detected from acceleration occurring anywhere that the field line connected to the observer is crossed by the shock front.

The fraction of time with ^{3}He present changed by at most a factor of ~ 2 over the 4.5 years included in our study. This relatively small change may be due, in part, to the contribution of galactic ^{3}He at MeV energies near solar minimum when there is a lower rate of SEP events. This galactic component, which should be much less significant at lower energies and at smaller heliocentric radii, probably is not making an major contribution to the source population being accelerated by interplanetary shocks.

A striking feature seen in the particle mass vs. time plots such as shown Figure 1 is the common occurrence of intervals in which ^{3}He is being detected by the SIS and/or ULEIS instruments at a rate of a only few particles per day. Previous studies [11, 12] have shown that ^{3}He energy spectra accumulated over many days of solar quite time exhibit low-energy turn-ups, indicating a solar (not galactic) origin of these particles. We suggest that the ^{3}He we are observing during such quite periods could be the result of a large number of impulsive SEP events with peak intensities too low to be detected as such with present instrument sensitivity. One gets a visual impression (Fig. 1) that the distribution of waiting times between ^{3}He particles is not the exponential expected if the flux were truly constant. A quantitative study of this distribution, which may help constrain the source of these particles, is beyond the scope of the present work.

While the present study shows that energetic ^{3}He is present in the interplanetary medium frequently enough to provide the seed material for acceleration by interplanetary shocks, further work will also be needed to establish whether the *quantity* of ^{3}He is also sufficient.

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